Ore Petrography and Geochemistry of some REE-bearing Fe-oxide Assemblages from the Idkerberget Deposit, Bergslagen, Sweden

Fredrik Sahlström
Table of Contents

1. Introduction ............................................................................................................................................... 7
2. Geological background .............................................................................................................................. 9
  2.1. Regional geology ................................................................................................................................ 9
  2.2. Metallogeny and mining in the Bergslagen area .................................................................................. 10
  2.3. Apatite-bearing iron oxide ores in Bergslagen ............................................................................... 11
  2.4. Idkerberget ore field ......................................................................................................................... 13
  2.5. Accessory minerals as REE-carriers ............................................................................................... 14
3. Sample preparation and analytical methods ............................................................................................ 15
  3.1. Sample preparation ........................................................................................................................... 15
  3.2. Analytical methods ........................................................................................................................... 16
    3.2.1. Ore microscopy ......................................................................................................................... 16
    3.2.2 SEM-EDS ................................................................................................................................... 16
    3.2.3 Electron microprobe (EMP) analysis ......................................................................................... 17
    3.2.4 Geochemical analysis ................................................................................................................. 18
4. Results ..................................................................................................................................................... 18
  4.1. Ore petrography ................................................................................................................................ 19
    4.1.1. KES112004A ............................................................................................................................. 19
    4.1.2. KES112001 .............................................................................................................................. 21
    4.1.3. KES112005A+B ........................................................................................................................ 27
    4.1.4. KES112002A-D ........................................................................................................................ 29
  4.2. Geochemistry .................................................................................................................................... 31
  4.3. Discussion ......................................................................................................................................... 32
    4.3.1 REE-mineralogy ........................................................................................................................... 33
    4.3.2 Geochemistry .............................................................................................................................. 33
5. Conclusions ............................................................................................................................................. 34
Acknowledgements ..................................................................................................................................... 35
References ................................................................................................................................................... 36
Abstract

The mine dumps of Kiruna-type apatite-iron oxide ore in Bergslagen, South Central Sweden, contain elevated amounts of rare earth elements (REEs). A recently started project at Uppsala University has been initiated to study these ores among others in order to document occurrences of REEs and other critical elements in the mine dumps. In this study a selection of samples from the Idkerberget deposit have been studied with respect to their geochemistry and petrography with a special focus on REE-bearing phases. In addition, their mining potential and their relationship to related ore deposits such as Blötberget, Grängesberg and Kiirunavaara have been considered. The bulk geochemistry of the ores was analyzed using ICP-ES and ICP-MS. Polished sections of the ore samples were studied using ore microscopy, SEM-EDS and WDS microprobe technique. The results indicate that the ores consist mainly of magnetite and hematite, with minor silicates, flourapatite, pyrite, chalcopyrite, monazite-(Ce), allanite-(Ce), thorium silicate, titanite and zircon. Most REEs were originally hosted in fluorapatite, but metamorphic and/or hydrothermal overprinting has resulted in complex textures and neomineralisation involving exotic REE-bearing minerals such as monazite-(Ce), allanite-(Ce) and secondary flourapatite. These features have also been observed in the related ore deposits nearby. The ores are enriched in REEs by factors between 1 and 9 compared to crustal values, with LREEs being the most enriched. These enrichments are rather low compared to other REE-ores currently being mined, but the easy access to the ores could mean that mining can be profitable with the current demand of these commodities.

Sammanfattning på Svenska

Varphögar av apatitjärnmalm av Kirunatyp ifrån järnmalmsbrytning i Bergslagen, Sydcentrala Sverige, innehåller förhöjda halter av sällsynta jordartsmetaller. Ett projekt vid Uppsala Universitet undersöker förekomster av sällsynta jordartsmetaller och andra kritiska element i
varphögar bland annat från apatitjärnmalmer. I denna studie har prover från ett av Bergslagens apatitjärnmalmsfält, Idkerberget, undersökts geokemiskt och petrografiskt med fokus på faser som innehåller sällsynta jordartsmetaller. Deras utvinningspotential och deras relation till liknande förekomster såsom Blötberget, Grängesberg samt Kiirunavaara har också tagits i beaktning. Bulkgeokemin i proverna analyserades med ICP-EM och ICP-MS. Polerprov av malmerna undersöktes medelst optisk mikroskopi, SEM-EDS samt med WDS-mikrosondteknik. Resultaten visar att malmerna framförallt består av magnetit och hematit, med mindre mängder silikater, flourapatit, pyrit, kopparkis, monazit-(Ce), allanit-(Ce), thoriumsilikat, titanit och zirkon. Sällsynta jordartsmetaller är i huvudsak bundna i flourapatit, men metamorfa och/eller hydrotermala processer har resulterat i ny bildningen av exotiska mineral såsom monazit-(Ce), allanit-(Ce), och sekundär flourapatit. Dessa egenskaper har även observerats i apatitjärnmalmer från andra platser. Proverna från Idkerberget har 1-9 gånger högre koncentration av sällsynta jordartsmetaller än jordskorpan generellt, och lätta sällsynta jordartsmetaller är de mest anrikade. Dessa halter är relativt låga jämfört med sällsynta jordartsmalmer som bryts i dagsläget, men eftersom materialet förekommer i enorma varphögar gör tillgängligheten att metallerna ändå kan utvinnas med vinst om efterfrågan på denna resurs består.
1. Introduction

The Bergslagen region in Central Sweden hosts a large variety of different iron and sulphide mineralizations, and has since medieval times played a large role in supplying metals both locally and internationally (Stephens 2009, Ripa & Kübler 2003). However, due to increasing international competition, the region saw a downfall in mining activity during the end of the 20th century, and only a couple of mines were left operational (Back, unpublished).

Nevertheless, in recent years there has been a resurge of interest in the area, and some of the abandoned iron mines are now targeted for re-opening (e.g. Dannemora, Grängesberg, Blötberget, Háksberg). But it might not be the large variety of base metals in the region that are of the highest value to the prospecting mining companies. The region hosts a previously known but not thoroughly investigated resource – rare earth elements (REE). In Western Bergslagen an apatite-iron oxide ore occurs, containing a variety of different accessory minerals that are enriched in REE. These minerals were unwanted during the iron mining, and were part of the gangue rock that was disposed of into the many mining waste piles present in the area (Fig. 1) (Högdahl et al 2012). However, due to the current dramatic increase in demand of these metals, yesterday’s waste could become the treasure of tomorrow, as mining companies and universities are investigating the possibilities of extracting REE from these old waste piles.

Fig. 1. Piles of old waste from iron mining in Bergslagen.

Picture from Staffan Huss blog.
REE consist of a chemically coherent group in the periodic table, namely the fifteen lanthanides plus scandium and yttrium. In geochemical processes their behaviour is very similar. During the last decades they have rapidly increased in importance due to their role as constituents in a wide variety of high technology applications (cf. Haxel et al. 2002). The Heavy Rare Earth Elements (HREE – Gd to Lu, Y) and Europium are the most scarce of the group and deposits containing high grades of these elements are considered the most valuable (Haxel et al. 2002).

Despite to their name, REEs are fairly common in the Earth’s crust with markedly higher concentrations than many sought-after industry metals such as nickel, copper and zinc. However, concentrated ore deposits of REEs are extremely uncommon, and present projects are limited to only a handful of locations in the world. There appear to be very few geological processes that can concentrate REEs into economical concentrations. Today’s most important ores seem to be confined to carbonatitic, peralkaline and pegmatitic intrusions, iron oxide deposits and lateritic weathering crusts developed on granitic-syenitic rocks (Haxel et al. 2002).

On top of the extreme scarcity of mineable REE deposits in the world, the availability of these important metals is decreased due to the fact that China today controls over 95 % of the world output of REE (Haxel et al. 2002). Because of factors such as low labour costs, very rich mineral resources and low mining infrastructure costs, China has been able to outcompete mines in other countries over the last couple of decades, such as the once so important Mountain Pass mine in California, USA (Beauford 2012). In 2012, news reports states that three other economic superpowers, the European Union, the United States and Japan has jointly filed a case with the World Trade Organization due to recent restrictions in the export of REE from China (Financial Post 2012). These events indicate what potential importance such resources could have for Sweden in the future, and research focused on assessing these ores and their genesis could help exploration worldwide for similar ore deposits as the demand of REE continues to increase.

In this thesis a suite of samples from the old mine dumps at the Idkerberget apatite-iron oxide mine in Western Bergslagen has been studied with a special focus on REE. Using ICP-MS, reflected light microscopy and electron microscopy with EDS and WDS their geochemistry and petrography has been investigated.
2. Geological background

2.1. Regional geology

The Bergslagen ore province is located in the South-Western part of the 1.9-1.8 Ga Svecokarelian domain in the Fennoscandian Shield (Stephens et al. 2009). It is an intensely mineralized part of a large felsic magmatic region of Early Proterozoic age, which has been metamorphosed in medium to high grade (Allen et al. 1996). The rocks in the area are dominantly part of a volcano-sedimentary succession containing sub-volcanic and volcaniclastic rocks of mainly rhyolitic composition deposited primarily in a submarine environment (Allen et al. 1996, Lundström 1987). Subordinate rock types in the area consist of intermediate and mafic volcanic rocks together with chemical, epiclastic and organogenic sedimentary rocks that can be found at various stratigraphic levels in the volcanic succession (Ripa & Kübler 2003).

The rocks were affected by Svecokarelian deformation and metamorphism to a variable extent, and parts of the western area also show indications of a tectonic overprint by the Sveconorwegian orogeny around 1.0 Ga (Stephens et al. 2009). The dominating structures are steep, tight to isoclinal, doubly plunging F₁ synclines that are most apparent in the supracrustal rocks (Allen et al. 1996).

The basement of these Svecofennian rocks is unknown. However, quartzites containing detrital zircons dated to 2.7-1.95 Ga occur locally (Lundqvist 1987). This suggests that an older granitic basement may underlie the Bergslagen region, and this basement was exposed to erosion contributing to the successive formation of the quartzites (Allen et al. 1996).

The rocks in the Bergslagen region are interpreted to have formed in an extensional setting, presumably in the back-arc area inboard of an active continental margin (Allen et al. 1996). The region is considered to have evolved through a magmatic-extensional-compressional cycle, which started with intense magmatism, thermal doming and crustal extension. This stage was followed by a period of waning extension, thermal subsidence, reversal from extension to compressional deformation, metamorphism and structural inversion (Allen et al. 1996). In addition,
superimposed on this cycle are second-order stratigraphic variations due to subregional variations in uplift and subsidence as well as variations in the evolution of individual volcanoes (Allen et al. 1996).

The Bergslagen region hosts a wide variety of different ore deposits, including banded iron formations, magnetite-calc-silicate skarn, manganiferous skarn- and carbonate-hosted iron ore, apatite bearing iron ore, stratiform and stratabound Zn-Pb-Ag-(Cu-Au) sulfide ores and W skarn (Allen et al. 1996). Most ores can be found in hydrothermally altered metavolcanic rocks and associated metalimestones and skarns. They often, with the apatite-bearing ores as an exception, occur in the upper part of the volcanic succession, in medial to distal facies, which links them to the waning volcanism stage and deposition in a subaqueous environment (Allen et al. 1996). It is possible that the ores are genetically linked to specific magmatic-hydrothermal systems from specific volcanoes (Allen et al. 1996).

### 2.2. Metallogeny and mining in the Bergslagen area

The Bergslagen ore province is one of the four major ore districts in Sweden, the others being the Skellefte district, Northern Norrbotten and the Caledonides. Bergslagen is historically the most important district, and the mining history dates back all the way to medieval times (Ripa & Kübler 2003). Bergslagen is famous for its sulphide deposits, and up until 2005 the nine major sulphide ore fields (production >1 Mt) in the region had produced around 100 Mt of ore (Åkerman 1994). One of the oldest, and possibly the most famous deposit in Bergslagen is the Falu mine (28 Mt) (Stephens et al. 2009). Here Sweden’s historically largest copper mine, the Falu Copper Mine, used to operate and during medieval times this mine supplied more than half of Europe’s copper. Zinc, lead, silver, gold and bismuth were also mined here, and the pyrite-rich mining waste is still used to produce the famous Falu red paint which is very commonly used on rural houses in Sweden. The mine was closed down in 1992, and became a World Heritage Site in 2002 (Falu gruvas miljöhistoria 2002). Today, only three base metal sulphide mines are active in the Bergslagen region, namely the Garpenberg Zn-Pb-Ag deposit, the Zinkgruvan Zn-Pb-Ag deposit and the Lovisagrivan Zn-Pb deposit (Stephens et al. 2009).
However, looking back through time it is clear that iron has played the largest role in the mining history of Bergslagen (Ripa & Kübler 2003). The region hosts 32 major iron deposits (production > 1 Mt) that up until 1993 have produced around 420 Mt of ore, and in total there are over 6000 iron occurrences found in Bergslagen (Åkerman 1994). The apatite-bearing iron oxide ores have accounted for around half of this production, and have been mined from five different ore fields (the Grängesberg, Blötberg, Fredmundsberg, Lekomberg and Idkerberget fields, Fig. 2; Ripa & Kübler 2003). Ore grades generally range between 49 and 53 % in Lekomberg and between 58 and 62 % in Blötberget, Grängesberg and Idkerberget. Phosphorus normally ranges between 0.6 to 1 %, with some reports of contents up to 8 %, and locally it was possible to mine apatite ore (Ripa & Kübler 2003, Geijer & Magnusson 1944). The largest was the Grängesberg field, which was mined between 1858 and 1989 with a total production of 150 Mt of ore with grades of 40-63 % iron (Åkerman 1994).

During the 60s and onwards the profitability of mining the Bergslagen iron ores decreased. This was due to reasons such as competition from cheap, high quality (less phosphorus and alkali) iron ores mined in open pit operations on other continents, infrastructural difficulties and loss of important Swedish costumers (Back, unpublished), and until now the iron mining activity in the region has been at somewhat of a standstill. However, renewed interests in the region has led to the recent re-opening of the Dannemora mine (dannemoramineral.se), and other re-openings of old mines such as Blötberget, Häksberg (Nordic Iron Ore) and Grängesberg (Grängesberg Iron AB) might follow in the near future, all of which has boosted research focus on these types of ores.

2.3. Apatite-bearing iron oxide ores in Bergslagen

The apatite-bearing iron oxide ores in Bergslagen differ in setting from the other ore types in the area, and they appear to be genetically different (Allen et al. 1996). The ores are mostly hosted in deformed dacitic to andesitic, feldspar-porphyrritic metavolcanic rocks, with metamorphic grades ranging from medium to upper amphibolite facies (Ripa & Kübler 2003). This is opposed to the skarn iron oxide ores and the BIF ores that are hosted in skarn-altered carbonate rocks and skarn
altered volcanic ash-siltstone (Ripa & Kübler 2003). The apatite-bearing iron oxide ores also seem to be found at a lower stratigraphical position than the other iron ores in the region (Allen et al. 1996). The ores consist of both magnetite and hematite (Ripa & Kübler 2003), of which magnetite is altogether dominant. In addition, the ores contain apatite and small amounts of quartz and calc-silicate minerals such as actinolite, epidote, chlorite and garnet (Frietsch 1975). The apatite-bearing iron oxide ores in Bergslagen are parallel to the north-east trending axial surface trace of the main synmetamorphic folds in the region (Fig. 2), suggesting that these structures and the formation of the ores could be linked together (Ripa & Kübler 2003).

Fig. 2. Bouger anomaly map of the Bergslagen region, with the apatite-iron oxide ore fields marked. Blue represents low density areas and red represents high density areas. White dotted lines indicate the interpreted lineaments. Figure from Ripa et al. 2003.
The apatite-bearing iron oxide ores of Bergslagen are part of a larger group of ores called “Kiruna-type” apatite-iron oxide ore deposits after the seemingly related deposit in Kiirunavaara, northern Sweden (Vogt 1927, Geijer 1931). The origin of these ore deposits is disputed, and has been widely debated over the last century. Two schools have evolved: those in favor of a magmatic origin and those in favor of a hydrothermal origin. The magmatic origin is supported by Weis (2011), Nyström et al. (2008), Frietsch (1978), Geijer (1931, 1967) and Asklund (1949) among others. They propose that the ores formed directly from an iron oxide magma, derived from a dacitic parental magma by liquid immiscibility. This magma was then erupted onto the surface as lava flows or emplaced at subvolcanic levels. On the other hand, various suggestions of a hydrothermal origin include exhalative-sedimentary bodies deposited in a marine environment proposed by Párak (1975, 1984), a metasomatic-hydrothermal origin proposed by Rhodes & Oreskes (1994, 1999) and Sheets (1997) and a replacement origin proposed by Sillitoe & Burrows (2002).

2.4. Idkerberget ore field

At Idkerberget the apatite-iron oxide ores occur as lenses along an amphibolite zone (Magnusson 1937). The amphibolites are banded and together with the ore they occur inside a gneiss of presumed felsic metavolcanic origin (Back, unpublished). Sharp contacts between the ores and the amphibolites has been stated to indicate that the amphibolites are intrusive in the ores (Magnusson 1937). Within the ore-bearing section numerous intense alteration zones and mylonite zones can be found, and faulting has occurred along at least two faults (Magnusson 1937, Back, unpublished). The ores are located in three different horizons, namely the amphibolite horizon, the impregnation horizon and the Väggruvan footwall ore zone (Sundius 1944). The ores mainly consist of magnetite, but minor hematite is also present, especially in the tips of the ore bodies (Back, unpublished). The total tonnage of the Idkerberget ore field comprised of 10 million tons of high grade ore grading 62 % Fe and 0.6 % P (Back, unpublished). According to Back (1983), the Idkerberget ore field is mined out, and no new ore discoveries are to be expected.
2.5. Accessory minerals as REE-carriers

The majority of the REEs in these types of ores are contained in accessory minerals, where the phosphates in particular play an important role (Bea 1996). In Kiruna-type iron ores the most common REE-carrying mineral is flourapatite, Ca_{10}(PO_4)_{6}(F,OH,Cl), with minor amounts of monazite-(Ce), (Ce,LREE,Th)PO_4, and more rarely xenotime-(Y), (Y,HREE)PO_4 and allanite-(Ce) (REE-rich epidote group mineral) are also present (Harlov et al. 2002). These phases are closely linked to each other, and both natural and experimental examples indicate that monazite can form from original host flourapatite due to metasomatic alteration (Harlov et al. 2005). Monazite is often present as small inclusions inside flourapatite, or as larger recrystallized grains along flourapatite grain boundaries or intergrown with magnetite and silicate minerals (Harlov et al. 2002). In flourapatite REE can substitute for Ca, with electrostatic neutrality maintained by substitution of Si for P or Na for additional Ca (Harlov et al. 2002). This is how the flourapatite gets enriched in REE. During high-temperature leaching flourapatite can become depleted in LREE, Si and Na due to a reverse reaction. These depleted regions appear darker than the unreacted flourapatite, and monazite can nucleate in these depleted regions (Harlov et al. 2002, Harlov et al. 2005). The formula for this reaction is as follows: (flourapatite 1)+Ca(in fluid)+P(in fluid)\rightarrow (flourapatite 2)+monazite+Si(in fluid)+Na(in fluid), where flourapatite 1 is enriched in LREE, Na and Si compared to flourapatite 2 (Pan et al. 1993). These processes play a large role in the REE-mineralogy of the ores in Idkerberget. Back (1983) analyzed the distribution of REE in samples from ore products and mining waste from Idkerberget and found that possibly over 70-75% of the REE were bound in monazite as compared to around 25-30 % in flourapatite.

Due to its unstable nature during fluid-rock interactions, monazite is often altered into various breakdown products such as allanite-(Ce), flourapatite and thorium silicates (Ondrejka et al. 2012).

The apatite in Kiruna-type ores in Fennoscandia commonly contain 2000-7000 ppm of REE and shows weak to moderate LREE/HREE fractionation and negative EU-anomalies (Frietsch & Perdahl 1995).
3. Sample preparation and analytical methods

3.1. Sample preparation

Five hand specimens (KES112005A+B, KES112004A, KES112001, KES112002A-D and KES112003) collected from various locations in the dumps at Idkerberget were provided for this study. All five samples were analyzed geochemically. Using the diamond rock saw at the Department of Earth Sciences, Uppsala University, slices of each hand specimen were cut out. The slices were on average 5*5 cm large, and unknown weathering minerals on the rock surfaces were cut off to avoid contamination in the analysis. Geochemical analyses were conducted at Acme Labs, Canada, using ICP-ES and ICP-MS technique.

Additionally, four samples (KES112005A+B, KES112004A, KES112001 and KES112002A-D) were cut and prepared as polished sections for reflected light microscopy, SEM-EDS and WDS analyses. From each specimen two polished sections were prepared. First, the hand specimens were cut into smaller pieces using the diamond rock saw at the Department of Earth Sciences, Uppsala University. The cut rock pieces were then ground and polished. Grinding was performed by rubbing the sample against a glass plate covered with silicon carbide powder mixed with water. This was done in four stages, and in each successive stage a finer grained powder was used. The grain size of the silicon carbide powder ranged from 80 µm to 45 µm to 18 µm and finally 12 µm. Most time was spent on the finer stages, and between each stage the samples were cleaned in an ultrasonic bath to make sure no contamination of coarser grains took place, which could lead to plucking. Before moving on to a fined grained powder the samples were inspected under the microscope to determine if they were ready.

After the grinding the samples were polished. This was performed using the polishing machine at the Department of Earth Sciences, Uppsala University. On the polishing machine three different cloths combined with diamond powder of different grain sizes were used in three successive stages. The grain sizes of the diamond powder were 6 µm, 3 µm and 1 µm, and between each stage the samples were cleaned in the ultrasonic bath and inspected under the microscope in order to determine if they were polished enough to continue the process.
When the samples were polished satisfactorily they were ready to be analyzed under reflected light microscope, the SEM-EDS and WDS.

### 3.2. Analytical methods

#### 3.2.1. Ore microscopy

The polished sections were studied using reflected light microscopy in order to investigate the ore mineralogy of the samples. The microscope used was a Nikon Eclipse E600 POL at the Department of Earth Sciences, Uppsala University. The microscope was connected to a camera/computer system which made it possible to take high quality photomicrographs of the studied sections.

#### 3.2.2 SEM-EDS

The SEM-EDS study was performed at the Evolutionary Biology Centre at Uppsala University. The Scanning Electron Microscope (SEM) used was a Carl Zeiss Supra 35-VP Field Emission SEM equipped with a Robinson backscatter detector, a varial pressure secondary electron (VPSE) detector for low vacuum conditions and an EDAX Apex-4 energy-dispersive spectrometor (EDS) detector. Before the SEM-EDS study could be performed, the samples needed to be made electrically conductive. Therefore they were coated with carbon by means of sputtering at the microprobe laboratory at the Department of Earth Sciences, Uppsala University.

The SEM works by using a finely focused electron beam which is being swept in a raster across the surface of the sample. When the electron beam impinges the sample surface, a variety of different signals are produced, including secondary electrons, backscattered electrons, characteristic x-rays, Auger electrons and photons of various energies. These signals are depending on various characteristics of the sample, such as chemical composition, surface topography and crystallography (Goldstein et al. 1975).

The SEM used in this study is using a detector for backscattered electrons (BSE), which is a very effective way of differentiating between different mineral phases. Minerals containing heavy
elements, i.e. elements of high atomic number, will backscatter electrons more effectively than minerals containing predominantly light elements. Therefore they will appear brighter on the screen, which makes it possible to differentiate between different mineral phases as well as compositional variations within the same mineral phase (Goldstein et al. 1981). Also present in this SEM is an EDS, which made it possible to do x-ray microanalysis and obtain spectrograms of the elemental contents of the various mineral phases in order to identify them. The EDS detector analyzes the entire x-ray spectrum released when the electron beam in the SEM reacts with the elements in the different minerals in the sample. Since different elements have unique atomic structures, they will have unique peaks on the x-ray spectrum (Goldstein et al. 1975). This allows different elements and their abundance within a mineral phase to be recognized, and a spectrogram of the mineral chemistry can be created. The SEM and the EDS was in this study used to get a preliminary identification and overview of the various mineral phases in the samples, and later a more thorough and precise analysis was then carried out with the microprobe. The SEM also has the possibility of taking photographs of the studied sections.

3.2.3 Electron microprobe (EMP) analysis

The Department of Earth Sciences at Uppsala University hosts a Jeol JXA-8530F Field Emission Electron Probe Microanalyzer, which was used for further investigation of the mineral chemistry of the ores. Due to time constraints only one of the samples, the KES112001, was analyzed. This sample was chosen because it contained by far the most interesting mineral phases and textures identified by SEM-EDS, and these needed to be examined further.

The microprobe uses very similar techniques as the SEM-EDS. A focused electron beam is swept over the sample surface to generate x-rays. Various signals are produced and picked up by detectors, and different images appear on the screen depending on which signal is used. In this study the backscattered electrons were used once again similarly to the SEM-EDS study. In addition, the microprobe is equipped with both EDS and WDS spectrometers. The WDS technique allows for a much higher resolution of the elemental composition of minerals compared to the EDS. However, it needs to be calibrated precisely for each of the elements in the mineral analyzed. In this study monazite was analyzed. The calibration values used came from an older study of monazites, so they were not completely optimum and yielded results with total
weight percentages of 96-98.5%. Although these results are not perfect, they are accurate enough to get a good overview of the monazite chemistry in the ores and to be used in this thesis. BSE images of the various mineral phases yielded much higher quality than obtained by the SEM at EBC.

3.2.4 Geochemical analysis

Geochemical analysis was carried out to determine the bulk geochemistry of the five samples. This was done at ACME Labs, Canada. Major oxides and several trace elements were analyzed by ICP-ES (Inductively Coupled Plasma Emission Spectrometry) after a Lithium metaborate/tetraborate fusion and dilute nitric digestion of 0.2 g of each sample. REE and refractory elements were analysed by ICP-MS (Inductively Coupled Plasma Mass Spectrometry) following the same decomposition procedure as for the major oxide and trace element analysis. Additionally, 0.5 g of each sample was digested in Aqua Regia and analysed for precious and base metals using ICP-MS (ACME Labs 2012).

In this study primarily the REE were of focus. The raw REE data was chondrite normalized using values from McDonough et al. 1995, and then plotted in a spider diagram. The results could then be compared to spider plots of REE-contents of apatite iron oxide ores in nearby ore fields (Blötberget and Grängesberg). The enrichment factors of all the REE compared to average crustal values in each sample were also calculated by dividing the sample values with the average crustal values.
4. Results

4.1. Ore petrography

4.1.1. KES112004A

KES112004A is a magnetite ore with bluish-greyish silicate bands. The polished samples were cut to include as much of the banding as possible. In the ore microscope several different ore phases can be identified lying as small inclusions within the silicate bands. Magnetite and pyrite are present as rather large grains, while chalcopyrite is present as very small and scattered grains (Fig. 3a-b). Larger magnetite grains sometimes have inclusions of pyrite and chalcopyrite (Fig. 3c). No hematite was found in the sample. The mineral proportions of the sample are approximately 75% silicates, 20% magnetite, 4% pyrite and 1% chalcopyrite.

In SEM some minor flourapatite could be observed in the silicate bands (Fig. 3d), and also some small zircon crystals were identified. No REE-bearing phases other than flourapatite could be found in the samples.
Fig. 3 a-d. Reflected light (a-c) and BSE (d) images of sample KES112004A.

a) Isolated magnetite grains inside a silicate band.

b) The three different opaque minerals occur in the samples: magnetite, pyrite and chalcopyrite.

c) Pyrite and chalcopyrite in a magnetite grain.

d) One of the few fluorapatite grains found in the sample. No other REE-bearing minerals were found inside or around the fluorapatites.
4.1.2. KES112001

KES112001 consists primarily of magnetite and hematite with minor flourapatite, titanite, monazite-(Ce) rutile, al la nite-(Ce) and various silicates. The sample has a rather homogenous appearance and shows no banding like some of the other samples, however it is the most flourapatite-rich of the samples studied. Magnetite is partly replaced by hematite to form “martite”, and is present as interconnected subhedral to anhedral grains. The grains are on average made up of around 70% magnetite and 30% hematite, with hematite mostly occurring at the edges of the grains and sometimes along specific crystallographic orientations within the magnetite (Fig. 4a). Within the non-opaque phases martite is often present as small inclusions (Fig. 4b).

When observed in the SEM and EMP, several interesting textures were identified, especially regarding the REE-bearing minerals. One very common texture is the presence of small monazite-(Ce) inclusions inside the larger flourapatite grains, giving them a spotted appearance (Fig. 4c). When the small monazite inclusions were enlarged, some indications of crystal faces and euhedral/subhedral growth were visible (Fig. 4d)
Fig. 4 a-d. Reflected light (a-b) and BSE (c-d) images of sample KES 112001.

a) Close up of a “martite” texture. Note that replacement takes place along certain crystallographic planes.

b) Overview of the sample showing martite and flourapatite. Martite is present as inclusions in flourapatite.

c) Close up of a flourapatite grain containing small monazite-(Ce) inclusions.

d) Very high magnification photograph of a monazite inclusion. Note the visible crystal faces indicating euhedral/subhedral growth of the inclusions.

Another monazite-(Ce) texture is also present at iron oxide grain boundaries (Fig. 5a-b), where much larger accumulations of monazite are found. In the iron oxide grains are also small amounts of flourapatite, which possibly is a secondary breakdown product of the monazite. When observed in detail in the microprobe, these larger monazite accumulations were internally heterogeneous, with some parts of the grains lighter in colour and some parts darker (Fig. 5c). WDS analysis was performed on BSE light and dark parts of the grains (Fig. 5c), and the results are presented in Table 1. Especially thorium varies between the two, with BSE lighter parts being
much more enriched in Th compared to the darker parts. Additionally, it can be concluded that all monazites are monazite-(Ce) with significant La and Nd. Presented in Fig. 6 is a plot of Th, U and Si vs. REE+P in the monazites, together with the solid solution lines of monazite-huttonite/thorite and monazite-cheralite (Ondrejka et al. 2012). It is visible that the BSE lighter monazite plot along the huttonite/thorite substitution line, which indicates a (Th,U)+Si \rightarrow REE+P substitution. The BSE darker monazite give a more mixed composition between the huttonite/thorite substitution line and the cheralite substitution line, where Ca+(Th,U) \rightarrow 2REE. Some small monazite grains inside iron oxide have been altered creating coronas of allanite-(Ce) (Fig. 5d).

Another interesting feature in this sample is the presence of a thorium-silicate, probably huttonite (ThSiO$_4$) or thorite with the same composition, which was found as small scattered grains surrounding a small iron oxide grain inside a silicate grain (Fig. 5e). This, together with the Th-substitution described above, is an indicator of high thorium conditions during the formation of these minerals. The mineral was found in an area of the sample with absence of flourapatite. Since there was no flourapatite nearby incorporating thorium into monazite, thorium was concentrated into an independent Th-silicate mineral instead. Unfortunately, no Pb was detected in the analyzed monazite, which prohibits age calculations and relating monazite growth to metamorphic/hydrothermal events in the region.
Fig. 5 a-e. BSE images by EMP (a-d) and SEM (e) of sample KES112001.

a,b) Monazite-(Ce) in an iron oxide grain surrounded by silicates. Minor fluorapatite is also present.

b) Close up of monazite showing internal zoning of the mineral in BSE light, Th-rich parts and BSE dark, Th-poor parts.

d) Close up of a small monazite grains inside iron oxide. A corona of allanite-(Ce) has formed around it.

e) A thorium silicate phase appears as small, scattered grains around an iron oxide grain inside silicates.
Table 1. WDS point analyses performed in light parts (4) and dark parts (2) of monazites in sample KES112001, reported as wt % oxides and apfu. All are monazite-(Ce) with significant La and Nd. Note especially differences in Th between light and dark parts.

<table>
<thead>
<tr>
<th>wt %</th>
<th>Monazite_1 light</th>
<th>Monazite_1 light</th>
<th>Monazite_1 dark</th>
<th>Monazite_2 light</th>
<th>Monazite_2 light</th>
<th>Monazite_2 dark</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2O5</td>
<td>28.13</td>
<td>27.96</td>
<td>28.51</td>
<td>28.05</td>
<td>27.92</td>
<td>28.06</td>
</tr>
<tr>
<td>SiO2</td>
<td>0.54</td>
<td>0.47</td>
<td>0.40</td>
<td>0.51</td>
<td>0.65</td>
<td>0.55</td>
</tr>
<tr>
<td>ThO2</td>
<td>0.76</td>
<td>0.88</td>
<td>0.03</td>
<td>0.97</td>
<td>0.98</td>
<td>0</td>
</tr>
<tr>
<td>UO2</td>
<td>0</td>
<td>0.01</td>
<td>0.03</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>Al2O3</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Y2O3</td>
<td>0.32</td>
<td>0.37</td>
<td>0.01</td>
<td>0.26</td>
<td>0.39</td>
<td>0.11</td>
</tr>
<tr>
<td>La2O3</td>
<td>20.70</td>
<td>18.79</td>
<td>19.55</td>
<td>20.45</td>
<td>19.25</td>
<td>19.63</td>
</tr>
<tr>
<td>Ce2O3</td>
<td>34.87</td>
<td>34.70</td>
<td>35.40</td>
<td>34.89</td>
<td>34.65</td>
<td>34.51</td>
</tr>
<tr>
<td>Pr2O3</td>
<td>1.91</td>
<td>2.25</td>
<td>2.11</td>
<td>1.69</td>
<td>2.10</td>
<td>2.18</td>
</tr>
<tr>
<td>Nd2O3</td>
<td>8.80</td>
<td>9.88</td>
<td>10.15</td>
<td>8.50</td>
<td>9.82</td>
<td>9.84</td>
</tr>
<tr>
<td>Sm2O3</td>
<td>0.71</td>
<td>0.80</td>
<td>0.73</td>
<td>0.82</td>
<td>0.82</td>
<td>0.84</td>
</tr>
<tr>
<td>Gd2O3</td>
<td>0.36</td>
<td>0.43</td>
<td>0.32</td>
<td>0.41</td>
<td>0.52</td>
<td>0.43</td>
</tr>
<tr>
<td>Tb2O3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dy2O3</td>
<td>0.03</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ho2O3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Er2O3</td>
<td>0.07</td>
<td>0.06</td>
<td>0.08</td>
<td>0.10</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>Yb2O3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lu2O3</td>
<td>0</td>
<td>0</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>CaO</td>
<td>0.22</td>
<td>0.17</td>
<td>0.15</td>
<td>0.24</td>
<td>0.19</td>
<td>0.69</td>
</tr>
<tr>
<td>PbO</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>0.12</td>
<td>0.07</td>
<td>0.64</td>
<td>0.44</td>
<td>0.16</td>
<td>0.40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>apfu</th>
<th>Monazite_1 light</th>
<th>Monazite_1 light</th>
<th>Monazite_1 dark</th>
<th>Monazite_2 light</th>
<th>Monazite_2 light</th>
<th>Monazite_2 dark</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Si</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Th</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>U</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Al</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Y</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>La</td>
<td>0.31</td>
<td>0.28</td>
<td>0.29</td>
<td>0.31</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>Ce</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>0.51</td>
</tr>
<tr>
<td>Pr</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Nd</td>
<td>0.13</td>
<td>0.14</td>
<td>0.15</td>
<td>0.12</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Sm</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Gd</td>
<td>0</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Tb</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dy</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ho</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Er</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Yb</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lu</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ca</td>
<td>0.01</td>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Pb</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fe</td>
<td>0</td>
<td>0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

|REE   | 1.01             | 1.01             | 1.00            | 1.00             | 1.01             | 1.00           |
|REE+Si| 0.99             | 0.99             | 0.99            | 0.99             | 0.89             | 0.89           |
|Other Cations| 0.02 | 0.02 | 0.03 | 0.03 | 0.02 | 0.04 |

Table 1. WDS point analyses performed in light parts (4) and dark parts (2) of monazites in sample KES112001, reported as wt % oxides and apfu. All are monazite-(Ce) with significant La and Nd. Note especially differences in Th between light and dark parts.
Fig. 6. Plot of the light and dark monazites-(Ce) in a Th+U+Si vs. REE+P substitution diagram from Ondrejka et al 2012. The light monazites plot along the huttonite/thorite substitution line, whereas the dark monazites give a mixed signal between huttonite/thorite substitution and cheralite substitution.
4.1.3. KES112005A+B

KES112005A+B is dominated by magnetite and has a fine whitish-bluish banding of silicate minerals and flourapatite. Magnetite occurs mostly as anhedral, interconnected grains, but also as small inclusions in the fine bands present in the sample. Within the bands magnetite inclusions appear to be elongated and aligned with the bands (Fig. 7a). Also present in the sample is a Ti-rich phase, possibly titanite (Fig. 7b).

In BSE it is clear that the flourapatite is somewhat different compared to other samples. The vast majority of the flourapatite grains contain no other REE-bearing minerals. However the small monazite-(Ce) inclusions present in the flourapatite in the KES112001 sample were found in some grains, but at a much lower abundance (Fig. 6c).

A few flourapatite grains within the bands are breakdown products after monazite (Figs.7d-e). These flourapatite grains are notably lighter in BSE than the primary crystals. The BSE lighter colour indicates that it is REE-enriched which is common for secondary flourapatite (Ondrejka et al 2012), compared to the BSE darker, primary flourapatite. All secondary flourapatite grains after monazite were found in the silicate rich bands. Flourapatite within the massive magnetite parts of the sample do not contain any of these textures.
Fig. 7 a-e. Reflected light (a-b) and BSE (c-f) images of sample KES112005A+B.

a) Silicate and fluorapatite band through the ore. Note the elongated magnetite inclusions present in the band.

b) An unidentified Ti-rich phase found in the sample.

c) Sparse monazite-(Ce) inclusions in fluorapatite.

d,e) Monazite-(Ce) breaking down to fluorapatite. The fluorapatite near the monazite is considerably BSE lighter than the fluorapatite further away.
4.1.4. KES112002A-D

KES112002A-D consists mainly of magnetite and hematite. The magnetite and hematite appear as “martite”, with magnetite making up around 80 % of the ore content (Fig. 7a). The martite grains are subhedral to anhedral and occur in interconnected masses. The sample contains white silicate bands. The bands contain martite inclusions together with minor flourapatite and chalcopyrite (Figs. 8b-c).

When studied in the SEM no REE-bearing minerals could be found other than flourapatite, which was rather abundant in the sample (Fig. 8c). Some of the flourapatite grains host inclusions of iron oxides (Fig. 8d).
Fig. 8 a-d. Reflected light (a-b) and BSE (c-d) images of sample KES112002A-D.

a) Overview picture showing magnetite and hematite as “martite”, with sparse flourapatite also present.

b) Silicate bands with inclusions of chalcopyrite and martite.

c) Silicate banding with iron oxide and flourapatite grains. The flourapatite is not associated with any other REE-bearing minerals in this sample.

d) Flourapatite together with iron oxide. The small BSE light inclusions are iron oxides.
4.2. Geochemistry

In the chondrite normalized REE-plot (Fig 9.a) the five samples from Idkerberget together with average crustal values can be seen, and for comparison a similar plot with results from nearby Grängesberg and Blötberget was borrowed from Jiao (2012) (Fig. 9b). The Idkerberget ores display a gently sloping trend indicating slight LREE/HREE fractionation, which is normal in crustal rocks, but also all have distinct europium anomalies. Ore samples from Grängesberg and Blötberget have the same overall pattern, however these ores appear to be more REE-enriched and also have more subtle europium anomalies.

Fig. 9 a-b. Chondrite normalized spider plots of the REE-content of Bergslagen apatite iron oxide ores.

a) Chondrite normalized REE-plot of the five Idkerberget samples, compared with average crustal values (collected from WebElements).

b) Chondrite normalized REE-plot of samples from Blötberget and Grängesberg for comparison. The figure is taken from Jiao (2012).
In Fig. 10 the enrichment factors of REE in the Idkerberget samples compared to average crustal rocks can be seen. Two of the samples (KES112002A-D and KES112003) show very little to no enrichment and plot around average crustal values. The other three samples plot between 2-9 times enrichment for most REE.

Fig. 10. Plot of enrichment factors for the five Idkerberget samples relative to average crustal values (collected from Webelements). A sample with crustal concentrations will plot along the y=1 line. Enriched samples plot above y=1, depleted samples below.
4.3 Discussion

4.3.1 REE-mineralogy

The REE-mineralogy is quite variable throughout the samples. Some contain no REE-bearing minerals except fluorapatite, while others displayed the array of REE-minerals and textures associated with ores from Kiirunavaara as described in Harlov et al. (2002). Both the first generation, small monazite inclusions inside fluorapatite grains, and the larger, presumably recrystallized monazite accumulations growing on other minerals such as iron oxides were present in some samples. Part of the textures found in the Idkerberget samples were found in nearby Grängesberg ores as well (Jonsson et al. 2012), indicating similarities in REE mineralogy. Overall, it seems like the Swedish Kiruna-type apatite-iron oxide ores are rather similar in their REE-mineralogy, but with minor local differences, possibly in part due to different degree of regional metamorphic overprinting.

The analyzed samples from Idkerberget have high abundances of thorium. The presence of thorium silicates as well as a certain degree of thorium substitution into the monazite structure indicates thorium rich conditions during the formation of the REE minerals. This is something that might be exclusive to the Idkerberget area since it has so far not been reported from nearby ores from Grängesberg and Blötberget.

Additionally, some of the many different breakdown products and textures of monazite described by Ondrejka et al (2012) were found in the samples, displaying the unstable nature of monazite during hydrothermal fluid-rock interaction.

4.3.2 Geochemistry

The similarity of the spider plots of the Idkerberget ores and the Grängesberg and Blötberget ores indicate that all the ores have similar REE-characteristics, with the exception that the ores from Idkerberget are less enriched overall in REE and have more pronounced negative europium anomalies. The characteristics also seem similar to the ones from related ores in Kiirunavaara (Frietsch & Perdahl 1995) indicating a close relationship in REE bulk geochemistry within the
Kiruna-type apatite-iron oxide ores. The negative europium anomalies are interesting in the debate regarding the origin of these types of ores, as this normally is a signal indicating a magmatic origin. During low oxygen fugacities, Eu$^{3+}$ can become reduced to Eu$^{2+}$, which is chemically similar to calcium. During fractional crystallization of plagioclase, Eu$^{2+}$ replaces Ca$^{2+}$ and is gradually removed from the magma, causing the negative anomaly in the spider plot of later crystallized phases (Troll 2008). However this only applies for fully magmatic systems, and it is still unclear if Idkerberget and similar Kiruna-type deposits belong to this group.

The enrichment factors of the different REE are relatively low, lying between 1-9 depending on sample and element, with averages of 2-5 times that of the average crust. Normally, a high grade REE-ore contains at least 2 % REE-oxides, with famous mines such as the Mountain Pass REE-mine in California, US, averaging 8-12 % REE oxides (Haxel et al. 2002). To reach these concentrations the enrichment factor would need to be much higher than the ones observed in the Idkerberget ores. Additionally, the most desirable REEs, HREE and Eu, are relatively low in concentration in the samples. However, at Idkerberget REE-bearing minerals are already concentrated in dumps and tailings and can directly be processed without mining underground, which greatly reduces the costs involved. This would allow mining companies to use ores of lower grade than those mined at Mountain Pass for example, and maybe it is possible to profitably use the mining waste in Bergslagen as a REE-source in the future, especially if the prices of these metals keep increasing. Additionally, if the iron mines at Blötberget and Grängesberg are re-opened, it could be possible to extract REE as well as phosphorus from the ores as secondary products in addition to the iron, increasing the economic profit made from the mining.

5. Conclusions

The Idkerberget apatite-iron oxide ore is very interesting geochemically as well as mineralogically/texturally regarding its REE-bearing phases, and shows both similarities and differences with other related ore deposits of the Kiruna-type. The variability in mineralogy and
textural relations may in part be due to the differences in post-formational history and degree of metamorphism affecting the respective deposits. Even though enrichment of REEs is relatively low, profitable extraction could be possible during the right circumstances. Further research on these ores is important since the worldwide exploration for REE-ores is very poorly developed, and it is possible that this ore type can be a valuable asset in the struggle of securing the world’s increasing demand of these metals.

Acknowledgements

I would like to thank my supervisors Dr. Karin Högdahl (UU) and Prof. Erik Jonsson (SGU,UU) for giving me the opportunity to work on this project, for providing the samples for the study and for all the help and support. To Dr. Jarek Majka (UU) I owe my gratitude for accompanying me to the SEM and EMP and answering all my questions and giving valuable advice. I want to thank Gary Wife (EBC) for all the help and support while I did my SEM-EDS studies. Hans Harrysson (UU) helped me carbon coat my samples and taught me how to use the microprobe and WDS spectrometer – thank you. Last but not least I want to thank Åke Rosén for teaching me how to prepare polished sections for ore microscopy.
References


